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## Technical Memorandum 79640

(NASA-TM-79640) THE SIGNIFICANCE OF GAMMA RAY OBSERVATIONS FOR NEUTRINO ASTRONOMY (NASA) 25 p HC A02/MF A01 CSCL 03A

N78-32948

Unclas
G3/89 33095

# The Significance of Gamma Ray Observations for Neutrino Astronomy

A Paper Presented at the 1978 Dumand Summer Workshop on High Energy Neutrino Astronomy at the Scripps Oceanographic Institute, August 1978

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September 1978



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# THE SIGNIFICANCE OF GAMMA RAY OBSERVATIONS FOR NEUTRINO ASTRONOMY

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## I. INTRODUCTION

Celestial γ-rays and neutrinos are formed in some of the same astrophysical interactions, but have important different properties; therefore, the study of both will reveal more than either individually. Many of the primary forces of change occurring in astrophysical processes may be most directly attacked with measurements of these radiations because they are emitted in the fundamental interactions which are involved. Phenomena which can be studied include the presence and dynamic effects of the energetic charged cosmic ray particles, element synthesis (although the neutrino energies involved there are much lower than those relevant to DUMAND), and particle acceleration. In addition, since γ-rays in the energy range from several MeV to at least $10^{12}$ eV and neutrinos both have very low interaction cross sections, they have a very high penetrating power and can reach the earth from almost any part of the galaxy or universe. Therefore, they retain the detailed imprint of spectral, directional and temporal features imposed at their birth, even if they were born in regions opaque to visible light and x-rays. Neutrinos, of course, are especially penetrating, allowing the study of regions inside stellar objects inaccessible even to γ-rays; however, because of their very small cross section, they are extremely difficult to detect relative to γ-rays. Gamma rays, in turn, are more difficult to observe than x-rays or most other forms of electromagnetic radiation because their cross section is small compared to that of these other radiations, and their intensity in terms of numbers of photons is relatively low. In spite of this, the first results from γ-ray astronomy are now beginning to emerge; and, as they do, great interest is evolving in γ-ray astrophysics and high-energy astrophysical phenomena in general.

As an example of an astrophysical problem on which both γ-rays and neutrinos have a very direct bearing, many current theoretical models of the central region of active galaxies involve the acceleration of very large numbers of relativistic particles whose interactions lead to $\gamma$-rays and neutrinos in similar numbers and with an intensity and energy spectrum directly related to the parent particles. Therefore, measurement of $\gamma$-rays and neutrinos from Seyfert, BL Lac, and very high-luminosity radio galaxies will provide significant information on the nature of these relativistic particles and the material in the galactic center. The intensity upper limits, and in at least two cases the positive results, already existing in high-energy $\gamma$-ray astrophysics would then provide the basis for neutrino intensity predictions as a function of the amount of the surrounding material in the galaxy and the primary relativistic particle energy spectrum. Alternate theories for these galaxies suggest that the high-energy $\gamma$-radiation is due primarily to other processes, such as, for example, Compton interactions. In this case, the neutrino flux would fall below the minimum consistent with relativistic particle matter interactions. As the $\gamma$-ray and neutrino characteristics of extraordinary galaxies become established, the observation of radiation from quasars in $\gamma$ rays and neutrinos should be a major step in revealing the nature of these objects. Finally, on the basis of the $\gamma$-ray measurements in our own galaxy, very specific neutrino flux predictions can be made for normal galaxies; and this subject will also be discussed here.

Gamma-ray and neutrino observations of compact objects will also be complementary in a similar way. Here, as above, the spectrum of the primary particles may possibly be obtained over a wider range of energy with both observations than either individually, since in the lower energy region neutrino observations are difficult due to atmospheric background, as well as the decreasing cross section with decreasing energy; and in the highest energy region, the $\gamma$-ray intensity would probably be too low to detect. Again, fluxes and limits already obtained are quite relevant, and results which should be obtained with the Gamma Ray Observatory (GRO) satellite would be very significant. In addition, for supernovae in particular, if it can be observed, a pulse of low energy neutrinos might serve as an alert for $\gamma$-ray and other telescope observations.

In the next sections, these subjects will be discussed to show in a general way the relationship between $\gamma$-ray and neutrino observations for at least some concepts of these astrophsyical objects. Existing $\gamma$-ray measurements will be summarized; and, in some examples, they will be used to set ranges or limits for neutrino fluxes for specific types of models, both to show the possibilities for separation between models and to aid in consideration of neutrino detector designs.

## II. EXCEPTIONAL GALAXIES

Of the phenomena to be discussed here, exceptional galaxies represent one of the greatest challenges for theoretical astrophysicists, and possibly the most likely source of study for neutrino astronomy (e.g., Eichler, 1978). For the purposes of the discussion here, Seyfert, BL LAC and exceptional radio galaxies will be considered, as well as QSO's, which will be assumed to be an appropriate part of this section on unusual galaxies--especially in light of recent results (Stockton, 1978).

Table I, taken from Fichtel et al., 1978b, provides information on the current situation in $\gamma$-ray astronomy for some of the objects which are thought to be the more likely candidates for $\gamma$-ray emission. CEN-A, a radio galaxy (Grindlay et al., 1975; and Hall et al., 1976), and 3C273, a Quasar (Swanenburg et al., 1978), have been established as $\gamma$-ray sources; and evidence exists that NGC 4151, a Seyfert, is also (Cocco et al., 1977; and Grami et al., 1977). Significant (in terms of the implications for neutrino astronomy) upper limits exist for several others. The most complete survey of the sky which exists in a reduced form is that of SAS-2 (COS-B has obtained a somewhat more sensitive survey for a few regions). Figure 1 shows the region of the sky viewed by SAS-2. For any possible source not listed in Table I, but within the region of the sky observed by SAS-2 and at least $10^{o}$ from the galactic plane, an upper limit of approximately $1\times10^{-6}$ photons (E>100 MeV)/(cm$^2$s) will exist for the shaded areas of Figure 1. Along the galactic plane, the upper limits will be somewhat higher.

Of most interest here is the possibility that at least some of these galaxies have very large numbers of relativistic nucleons which are interacting with matter to produce unstable $\pi$ mesons which decay into neutrinos and $\gamma$-rays. It must be kept in mind, however, that other mechanisms have been proposed to explain the major part of the radiation. For example, the continuum radiation from Seyferts has been explained (e.g., Neugebauer et al., 1976) as a combination of synchrotron radiation, stellar emission and reradiation from dust. The nonthermal-emission process involved in BL Lac objects has been interpreted to be incoherent synchrotron radiation (Stein et al., 1976). The x- and $\gamma$-radiation

TABLE 1

| OBJECT | COORDINATES (DEGREES) R.A. | DEC. | b | l | DESCRIPTION | ENERGY | GAMMA RAY INTENSITY OR LIMIT (PHOTONS)/(cm$^2$s) | REF. |
|---|---|---|---|---|---|---|---|---|
| CEN-A | 200.5 | -42.7 | 309.4 | 19.5 | RADIO GALAXY | (0.1-10)MeV | $\sim 0.15\times10^{-2}$ | 1 |
| | | | | | | > 100 MeV | $< 1.3\times10^{-6}$ | 2 |
| | | | | | | > $3\times10^{11}$ eV | $(4.0\pm1.0)\times10^{-11}$ | 3 |
| CYG-A | 299.2 | 40.6 | 76.1 | 5.9 | RADIO GALAXY | > 100 MeV | $< 1.4\times10^{-6}$ | 2 |
| M87 | 187.0 | 12.7 | 283.5 | 74.5 | RADIO GALAXY | > 100 MeV | $< 0.5\times10^{-6}$ | 2 |
| 3C 273 | 186.2 | 2.2 | 289.0 | 64.1 | QUASAR | 50-500 MeV | $(1.5\pm0.4)\times10^{-6}$ | 4 |
| | | | | | | > 100 MeV | $< 1.3\times10^{-6}$ | 2 |
| 3C232 | 148.8 | 32.6 | 194.2 | 52.3 | QUASAR | > 100 MeV | $< 4.0\times10^{-6}$ | 2 |
| 3C323.1 | 186.8 | 21.0 | 264.0 | 81.9 | QUASAR | > 100 MeV | $< 0.4\times10^{-6}$ | 2 |
| NGC 4151 | 182.0 | 39.7 | 155.0 | 75.0 | SEYFERT | (.15-20) MeV | $(2-5)\times10^{-2}$ | 5 |
| | | | | | | > 1 MeV | $0.7\times10^{-3}$ | 6 |
| | | | | | | > 100 MeV | $< 0.7\times10^{-6}$ | 2 |
| 3C 120 | 67.5 | 5.3 | 190.2 | -27.5 | SEYFERT | > 100 MeV | $< 1.0\times10^{-6}$ | 2 |
| NGC 4051 | 180.0 | 44.8 | 149.2 | 70.0 | SEYFERT | > 100 MeV | $< 1.3\times10^{-6}$ | 2 |
| NGC 6814 | 294.5 | -19.5 | 29.1 | -15.6 | SEYFERT | > 100 MeV | $< 0.8\times10^{-6}$ | 2 |
| MK 509 | 310.4 | -10.9 | 36.0 | -29.9 | SEYFERT | > 100 MeV | $< 1.4\times10^{-6}$ | 2 |
| BL LAC | 330.0 | 42.0 | 92.5 | -10.4 | BL LAC | > 100 MeV | $< 1.2\times10^{-6}$ | 2 |
| MK 501 | 253.0 | 39.8 | 63.5 | 38.9 | BL LAC | > 100 MeV | $< 1.3\times10^{-6}$ | 2 |
| MK 421 | 164.2 | 38.4 | 180.1 | 64.9 | BL LAC | > 100 MeV | $< 0.9\times10^{-6}$ | 2 |
| 1912+30.5 | 288.0 | 30.5 | 67.8 | 9.0 | BL LAC | > 100 MeV | $< 1.0\times10^{-6}$ | 2 |
| 0548-32.2 | 87.0 | -32.2 | 237.4 | -26.3 | BL LAC | > 100 MeV | $< 2.6\times10^{-6}$ | 2 |

1. Hall et al., 1976
2. Hartman et al., 1978
3. Grindlay et al., 1975
4. Swanenburg et al., 1978
5. Cocco et al., 1977
6. Schönfelder, 1978

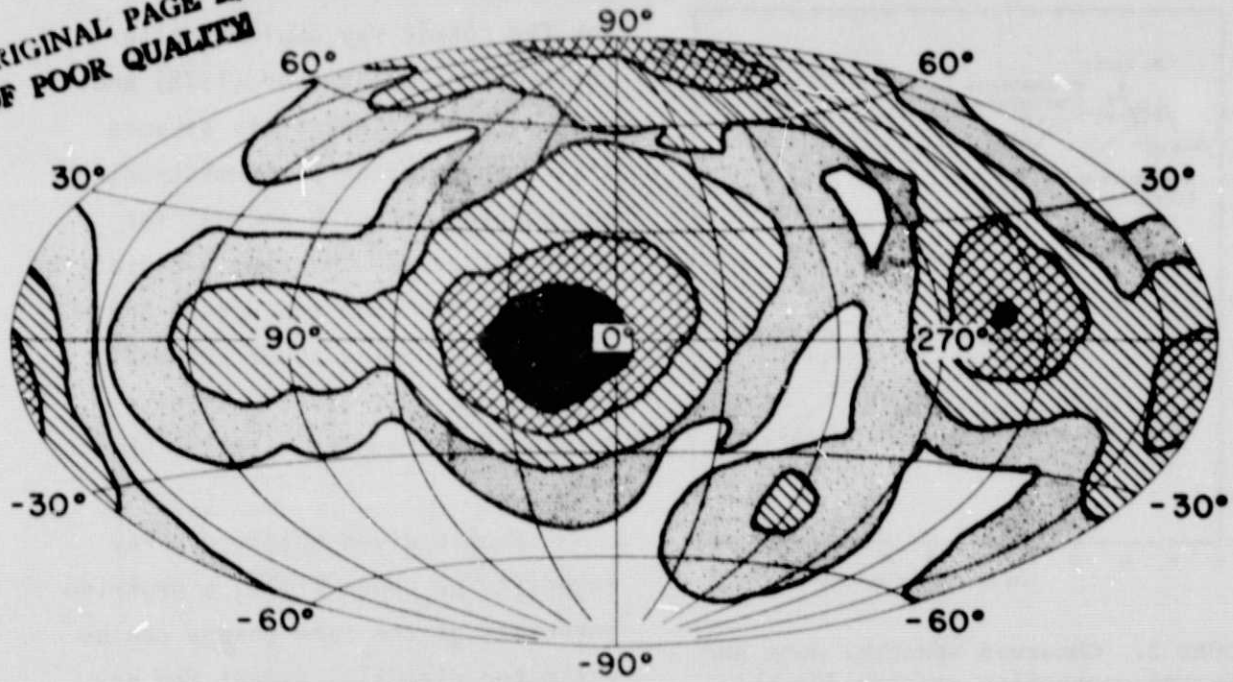


FIGURE 1: Regions of the sky viewed by SAS-2 in galactic coordinates at the sensitivity levels indicated in the figure.

- $1.9\times10^{7}-2.5\times10^{7}\,cm^{2}s$
- $1.2\times10^{7}-1.9\times10^{7}$
- $6.2\times10^{6}-1.2\times10^{7}$
- $1.9\times10^{6}-6.2\times10^{6}$
- $<1.9\times10^{6}$

observed from the radio galaxy CEN-A has been interpreted as being a combination of synchrotron and Compton radiation (Grindlay, 1975). Figure 2 shows the predictions for the spectra of CEN-A from this particular model.

With this warning regarding the alternate theoretical interpretations of the observed radiation, the implications of a relativistic particle matter interaction model will be explored, particularly for neutrino and γ-ray production, and interpreted in the light of γ-ray results already at hand. In a very high energy proton-proton collision, the majority of the energy not retained by the proton goes into the creation of mesons. The relevant calculations will not be reviewed in detail here; rather, the reader is referred to the previous paper (Stecker, 1978) of this conference. For a distribution of parent proton energies, the spectra of the secondary γ-rays and neutrinos will obviously be essentially the same and the numbers will differ by only a small factor. For the specific case of a cosmic ray

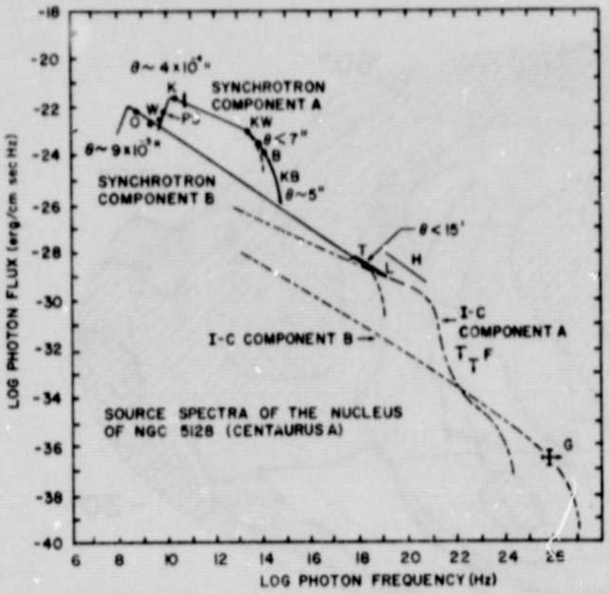


FIGURE 2: Observed spectral data and inferred connecting spectra for the nucleus of NGC 5128 (CEN-A). Marked points are the results given by O, O'Sullivan (1974); W (two points), Wade et al. (1971); PS, Price and Stull (1973); K (two points, where the vertical line connects the flux observed 1974, March 27 and 28), Kellermann (1974); KW, Kleinmann and Wright (1974); B (two points), Becklin et al. (1971); KB (heavy curve), Kunkel and Bradt (1971); T and L (connecting heavy curve), Tucker et al. (1973), and Lampton et al. (1972); H, Hall et al. (1975); F, Fichtel et al. (1975a); and G, Grindlay et al. (1975). Available data for the source angular diameter $\Theta$ are given. The data up through the x-ray spectrum are well-described by the sum of two synchrotron spectra A and B with assumed cutoffs (dashed curves) at $\sim 10^{14}$ Hz and $\sim 3 \times 10^{18}$ Hz, respectively, as described by Grindlay (1975). The source component angular diameters shown are appropriate to synchrotron self-absorption at the turnover frequencies ~30 GHz (A) and ~600 MHz (B) and the calculated inverse compton (I-C) spectra from each component, which are shown by the dot-dashed curves.

energy spectrum, the source functions for the cosmic ray nucleon matter interactions of Stecker (1978) are used. In addition, it is assumed that a combination of bremsstrahlung and Compton emission account for about 40% of the observed γ-radiation above 100 MeV from the Galaxy and are dominant below about 200 MeV (Fichtel et al., 1976; Kniffen, Fichtel and Thompson, 1977). See Figure 3.

From a given observed γ-ray intensity or upper limit, a neutrino intensity at the same energy can be estimated directly, except for any absorption and secondary production effects related to a thick absorber or a thick production region. To predict the neutrino intensity at a different, and in the case relevant here higher energy, the parent relativistic particle spectrum must be known. In some cases reasonable estimates can be made, and in others it is only possible to give tentative intensity estimates based on a range of assumed energy spectra. The nuclear composition of the relativistic particles is not an important factor unless it differs dramatically from the local cosmic ray composition, and even then it would not be a very major factor.

It is important here to clarify a possible misconception that γ-rays are easily absorbed. In fact, including the effects of secondary production from both the secondary protons and electrons, the intensity of γ-rays increases as a function of depth in a uniform material model with no significant charged particle curvature (due, for example, to strong magnetic fields) essentially linearly for more than one mean free path (about 33 g/cm$^2$ in hydrogen), and does not reach a maximum for over two mean free paths. This feature is illustrated in Figure 4 for air ($E_\gamma$> 30 MeV), wherein the calculations have been performed in great detail. The mean free path for air is about 30 g/cm$^2$. It is not before several mean free paths are reached that the ratio of high-energy neutrinos to γ-rays with $E_\gamma$> 30 substantially exceeds the thin target ratio.

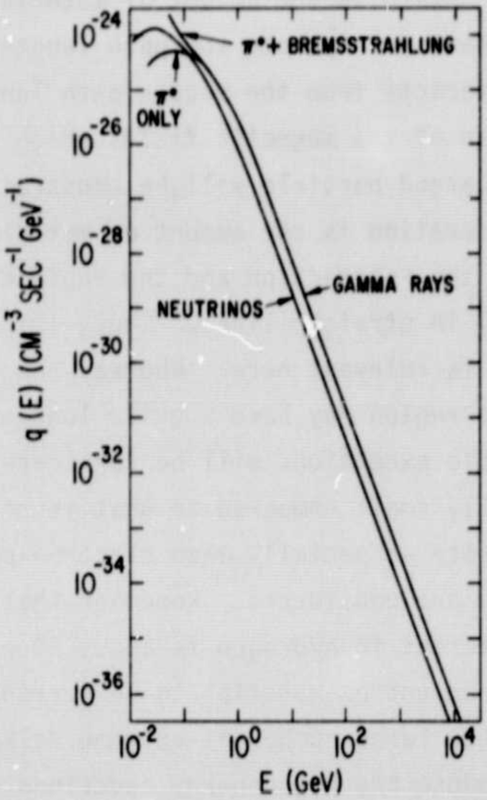


FIGURE 3: Gamma-ray and muon neutrino source functions calculated by Stecker (1978) for cosmic ray nucleon, matter interactions with the addition of the contribution from Bremsstrahlung (Kniffen, Fichtel and Thompson, 1977). The total neutrino plus antineutrino source function for both electrons and muons is assumed to be three times the value of the neutrino curve (Stecker, 1978).

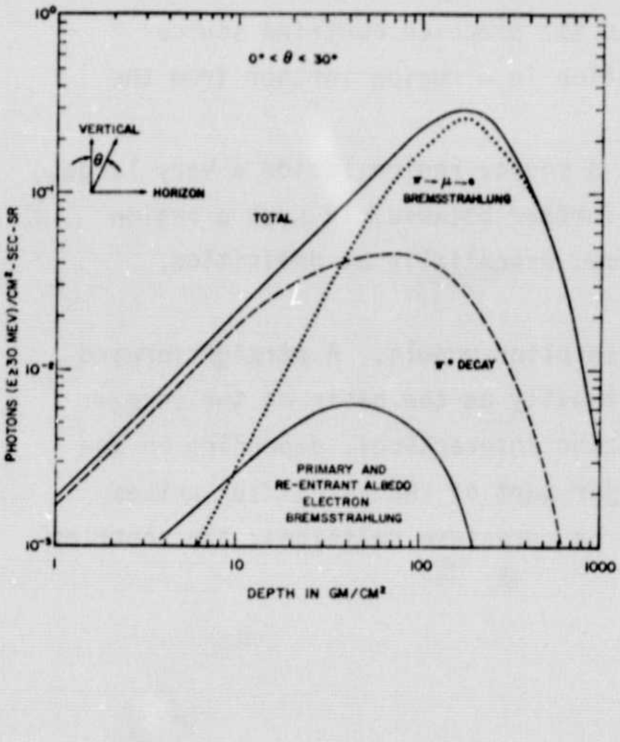


FIGURE 4: Calculated flux of γ-rays with E≥30 MeV as a function of atmospheric depth for an average zenith angle of 16° (Thompson, 1973).

Regarding the amount of material in the source region, it is also important to separate the path length of the primary charged particle before it interacts from the escape path length of the neutrino or γ-ray secondary. Because of the magnetic fields which exist in most astrophysical situations, the charged particle will be constrained in its motion and the relevant consideration is the amount of material along the complex curved trajectory. After the interaction and the rapid decay, the secondary neutrinos and γ-rays travel in straight lines. Thus, it is the line-of-sight column density which is relevant here. Whereas the charged particles confined to a source region may have a quite long mean path length normally, and although possible exceptions will be considered, the line-of-sight column density is normally small compared to what is required to significantly reduce the γ-ray intensity--especially when electron-photon cascades for the higher energy γ-rays are considered. Remember that the mean-free path for $10^2$ MeV γ-rays to interact in hydrogen is about 90 g/cm$^2$--implying in most cases a very large amount of material to be surrounding a volume large enough to contain the very large number of extreme relativistic ($E \gtrsim 10$ TeV) particles needed to produce the high-energy neutrinos of interest. Some models of small volumes, even on a galactic scale, have been proposed and even discussed at this meeting.

It should possibly be noted that x-ray data from active galaxies show little or no evidence for absorption--certainly nothing to imply amounts of material which would inhibit γ-rays. Of course, it may well be the x-rays are arising from a different region than the proposed neutrino source (e.g., the x-rays could be due to accretion in a region further from the center).

In the remaining discussion here, a source region inside a very large, very thick disk will not be considered further because, if such a region should exist, high-energy γ-ray astronomy, essentially by definition, cannot speak to it.

In the absence of such extreme absorption models. A straightforward estimate can be made for the neutrino itensity on the basis of the γ-rays resulting from relativistic particle matter interactions, depending on the particle spectrum. Remember, if the major part of the γ-ray flux arises in another way such as Compton emission or curvature emissions, the neutrino estimates will be much lower.

Neutrinos of all types, $\nu_\mu$, $\nu_{\bar{\mu}}$, $\mu_e$, and $\mu_{\bar{e}}$, together will have a source function approximately equal to that of the $\gamma$-rays, as noted earlier. Hence, the $\gamma$-ray upper limits, and in a few cases the observed intensities of about $10^{-6}$ photons/(cm$^2$s) above 100 MeV, imply a similar intensity or limit for the neutrinos at 100 MeV.

For relativistic particles with an energy spectrum of the same form as the cosmic rays, above 1 TeV the total neutrino plus antineutrino upper limits would be about $3\times10^{-13}$ $(\nu+\bar{\nu})$'s/(cm$^2$s), and above 10 TeV about $0.8\times10^{-14}$ $(\nu+\bar{\nu})$'s/(cm$^2$s). For a $10^9$ ton detector such as DUMAND, with an ideal 100% detection efficiency for every neutrino or antineutrino that interacts, the effective cross section multiplied by one day is approximately $1\times10^9$ s cm$^2$ for $E_\nu$>1 TeV and $3\times10^9$ s cm$^2$ for $E_\nu$>10 TeV, depending slightly on the energy spectrum, and about 1/3 and 1/2 these values, respectively, for antineutrinos. Assuming equal numbers of neutrinos and antineutrinos, the upper limits would be about $2\times10^{-4}$ detected $(\nu+\bar{\nu})$'s/day above 1 TeV and $2\times10^{-5}$ detected $(\nu+\bar{\nu})$'s/day above 10 TeV. If the parent relativistic particles are assumed to have a power law as flat as $dN/dE \propto E^{-2.2}$ in the relevant energy range rather than the steeper cosmic ray spectrum, these general upper limits could be increased to approximately $1.5\times10^{-2}$ detected $(\nu+\bar{\nu})$'s/day above 1 TeV and $4\times10^{-3}$ detected $(\nu+\bar{\nu})$'s/day above 10 TeV. An exponent which is significantly smaller than 2.2 would lead to $\gamma$-ray intensities above $10^{11}$ eV, which would be in conflict with upper limits set for a major part of the $\gamma$-ray sky (Weekes, 1978).

It is, of course, also important to know the background intensity level to determine the intensity levels predicted for various assumptions that can be seen above the background. The principal source of neutrinos of concern for a detector on the Earth is the cosmic ray interactions in the atmosphere. Berezinsky (1977) determined that the flux of these neutrinos would be approximately $2\times10^{-8}$ $(\nu+\bar{\nu})$'s/(cm$^2$ s ster) above 1 TeV and $1\times10^{-10}$ $(\nu+\bar{\nu})$'s/(cm$^2$ s ster) above 10 TeV. The rates predicted by the 1978 DUMAND study proposal are in close agreement with these figures . If it is assumed that DUMAND can determine the arrival direction to within $3\times10^{-4}$ ster (a circle with approximately a $1/2^o$ radius), then the relevant background to be compared with the point source levels would be: $6\times10^{-12}$ $(\nu+\bar{\nu})$'s/(cm$^2$ s) above 1 TeV and $3\times10^{-14}$$(\nu+\bar{\nu})$'s/(cm$^2$ s) above 10 TeV, or about $4\times10^{-3}$ detected $(\nu+\bar{\nu})$'s/day and $7\times10^{-5}$ detected $(\nu+\bar{\nu})$'s day, respectively. Thus, crudely, if the source is strong enough to be seen in a year's observing time, it should be above these background levels if the angular resolution will be as it was assumed to be.

As noted earlier, a quasar, 3C273, has now been seen in high-energy $\gamma$-rays. Assuming this source has a spectrum of the form $dN_\gamma/dE \propto E^{-2.2}$ as the optical, x-ray and $10^2$ MeV $\gamma$-ray data suggest and that it is limited at very high energies (Weekes, 1978), then the neutrino flux would be such that there would be of the order of $1\times10^{-2}$ detected $(\nu+\bar{\nu})$'s/day above 1 TeV and $2\times10^{-3}$ detected $(\nu+\bar{\nu})$'s/day above 10 TeV.

For Cen A (see Figure 2), Grindlay et al. (1975), observed $(4.1\pm1.0)\times10^{-11}$ photons $(E<3\times10^{11}\,eV)/(cm^2\ s)$. Assuming that this might imply an intensity of about $1\times10^{-11}$ photons $(E>1\ TeV)/(cm^2\ s)$ and a power law of the order of $dN/dE \propto E^a$, where $2<a<2.5$, a neutrino detection rate of about $0.6\times10^{-2}$ detected $(\nu+\bar{\nu})$'s/day above 1 TeV might be expected. Eichler (1978) has obtained a similar result. Remember, however, as noted earlier that a Compton synchrotron explanation for the observed x-ray and $\gamma$-ray emission from this source has also been proposed (Grindlay, 1975).

The information currently available on NGC4151 is shown in Figure 5. Unless there is an additional high energy component, as there apparently is for CEN-A, the spectrum would suggest that this is not a likely high energy neutrino source. Several possible explanations for the spectral shape exist, including unresolved $\gamma$-ray lines and accretion.

The estimated intensities and upper limits should be viewed as being very uncertain; however, with modest directional accuracy, the larger estimates at least are above the atmospheric background level (Silberberg and Shapiro, 1977; Berezinsky, 1977; Margolis, Schramm and Silberberg, 1978) and measurable with a year or two of observations. Better estimates will be possible when a much larger high energy $\gamma$-ray telescope is flown on the Gamma Ray Observatory (GRO). Not only will this telescope be well over an order of magnitude more sensitive than earlier ones, but also it should be able to make $\gamma$-ray measurements on strong sources to about $10^{10}$ eV or better, greatly reducing the energy range over which an extrapolation must be made.

## III. NORMAL GALAXIES

For normal galaxies, a general upper limit from $\gamma$-ray measurements of $10^{-6}$ photons $(E>100\ MeV)/(cm^2\ s\ ster)$ again applies for much of the sky.

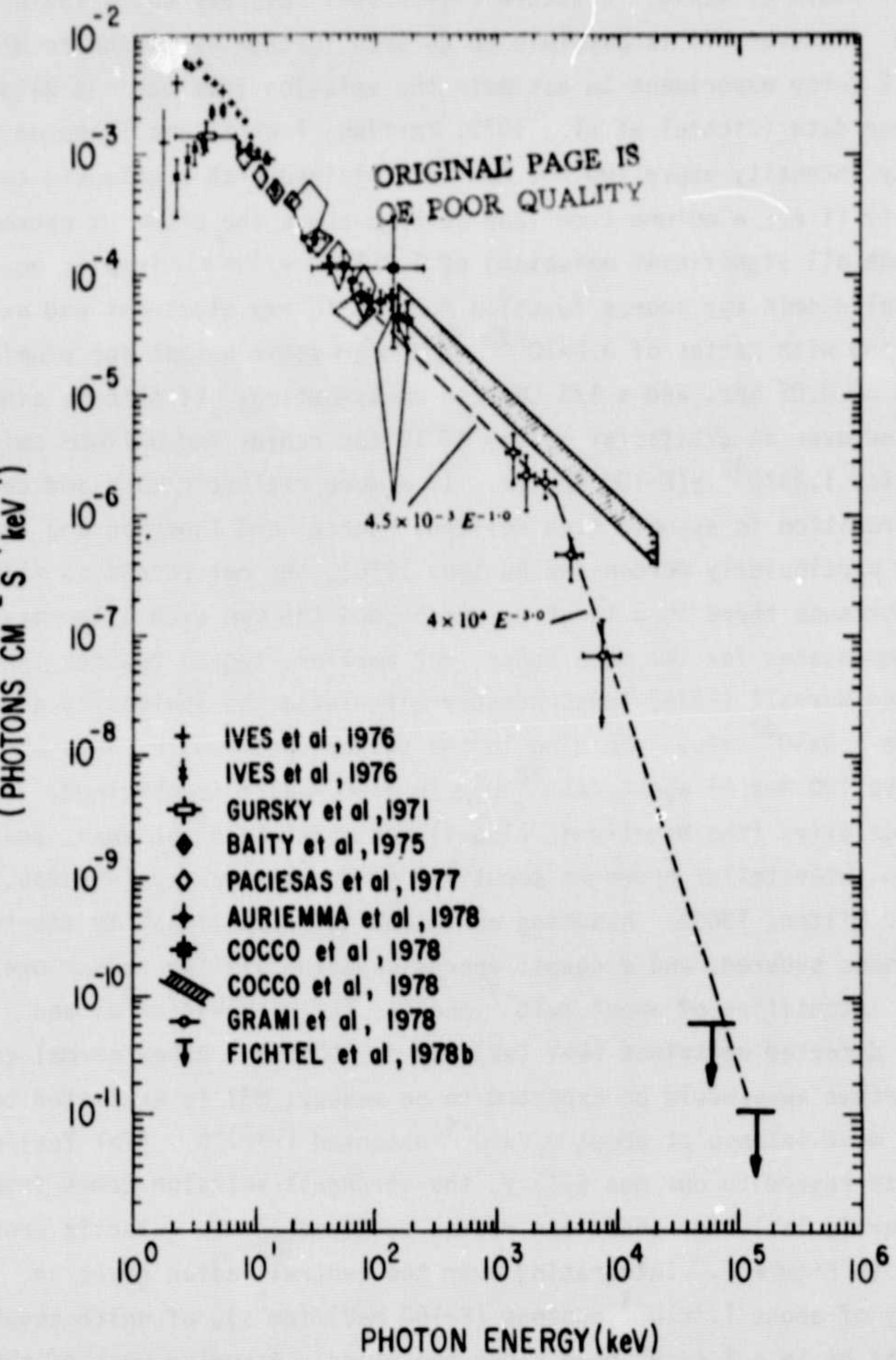


FIGURE 5: X and gamma intensities observed from NGC 4151 (adapted from Auriemma et al., 1978 and Schonfelder, 1978).

Assuming the cosmic ray spectrum to be similar to that in our own galaxy, the upper limit of $<2\times10^{-4}$ detected $(\nu+\bar{\nu})$'s (E>1 TeV)/day would again be obtained. However, it is possible to go even further using the results of the SAS-2 $\gamma$-ray experiment to estimate the emission from our own Galaxy. With these data (Fichtel et al., 1975; Kniffen, Fichtel and Thompson, 1977), the $\gamma$-ray intensity above 100 MeV can be explained with a galactic column emissivity (i.e., a column 1 $cm^2$ and as high above the plane as necessary to include all significant emission) of $1.7\times10^{-4}$ $\gamma/(cm^2 s)$. This is equivalent to a local cosmic ray source function for cosmic ray electrons and nucleons interacting with matter of $3.5\times10^{-25}$ $\gamma/(cm^2 s)$, a scale height for atomic hydrogen of 0.05 kpc, and a 12% Compton contribution. If this is simply integrated over an artificial galaxy of 16 kpc radius and uniform emissivity, one obtains $1.2\times10^{42}$ $\gamma$(E>100 MeV)/s. If a more realistic mass and cosmic ray distrubition is assumed (see Kniffen, Fichtel and Thompson and references therein, particularly Gordon and Burton, 1976), the net result is slightly smaller because there is a large volume beyond the sun with a low mass density which compensates for the more dense, but smaller, region towards the center. Strong and Worrall (1976) independently calculated the luminosity above 100 MeV to be $1.3\times10^{42}$ $\gamma/s$. Folding in the energy spectrum, a $\gamma$-ray energy flux above 100 MeV of about $7\times10^{38}$ ergs ($E_\gamma$>100 MeV)/s is obtained. The closest galaxies (the Magellenic clouds) are about $6\times10^4$ pc away, and have a mass in interstellar hydrogen about 1/3 of our own Galaxy (Hindman, 1967; McGee and Milton, 1968). Assuming an intensity proportional to the interstellar mass squared, and a cosmic energy spectrum similar to our own, leads to intensities of about $3\times10^{-7}$ photons (E>100 MeV)/($cm^2$s) and $0.6\times10^{-4}$ detected neutrinos (E>1 TeV)/day for DUMAND. Other normal galaxies, being further away, would be expected to be weaker; M31 is estimated to be the next most intense at about $0.2\times10^{-4}$ detected $(\nu+\bar{\nu})$'s (E>1 TeV)/day.

With regard to our own Galaxy, the strongest emission comes from the plane, particularly for about one radian centered on the galactic center, as shown in Figure 6. Integrating over the central radian gives an intensity of about $1.1\times10^{-4}$ photons (E>100 MeV)/($cm^2$s), of which about half might be in a 2 or $3^0$ band along the plane. Assuming most of this radiation to be due to cosmic ray matter interactions rather than compact objects (e.g., Hartman et al., 1978), and the bremsstrahlung and Compton contribution mentioned earlier, approximately $1\times10^{-2}$ detected $(\nu+\bar{\nu})$'s/day

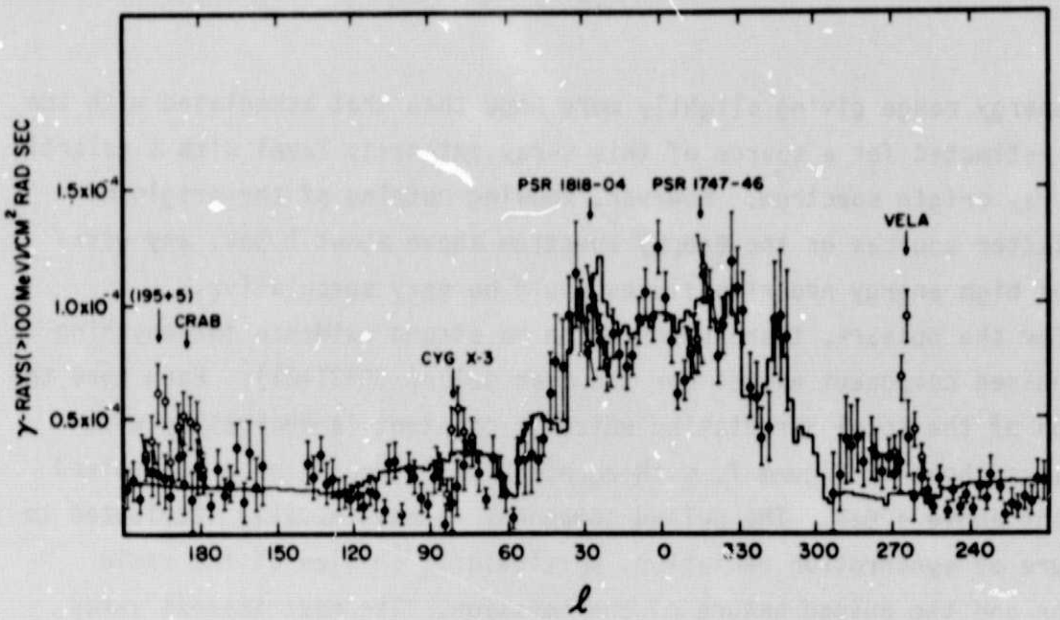


FIGURE 6: Intensity of γ-radiation above 100 MeV along the galactic plane integrated from b = -10° to b = +10° (Fichtel et al., 1975), together with an estimate of the part of the γ-rays resulting from cosmic ray matter interactions shown as the solid line (Kniffen, Fichtel and Thompson, 1977).

for E>1 TeV and $1\times10^{-3}$ detected $(\nu+\bar{\nu})$'s/day for E>10 TeV would be expected in this band. In this case, however, the background plays a bigger role since the radiation is along a band one radian long rather than from a point source. The atmospheric neutrino background would be of the order of $5\times10^{-1}$ detected $(\nu+\bar{\nu})$'s/day above 1 TeV and $1\times10^{-2}$ $(\nu+\bar{\nu})$'s/day above 10 TeV for this band and the detector assumption used previously.

## IV. COMPACT OBJECTS

There are only a limited number of objects which have been clearly identified as γ-ray sources. These include three, and possibly four, radio pulsars (Browning et al., 1973; Albats et al., 1972; Helmkin and Hoffman, 1973; Parlier et al., 1973; McBreen et al., 1973; Kinffen et al., 1974; Thompson et al., 1975; Ogelman et al., 1976; Thompson et al., 1976; Thompson et al., 1975a and 1975b; Bennett et al., 1977), Cygnus X-3 (Lanb et al., 1977), and several sources (Thompson et al., 1977a; Hermsen et al., 1977) not clearly identified with objects observed at other wavelengths. Relatively little can be said about these latter objects, all of which have intensity levels near $10^{-6}$ photons (E>10 MeV)/(cm$^2$s). One or two of them, such as (195,5), appear to have energy spectra that are relatively hard compared to the galactic plane in the 35 MeV to 1 GeV γ-ray energy range giving slightly more hope than that associated with the fluxes estimated for a source of this γ-ray intensity level with a galactic cosmic ray origin spectrum. However, knowing nothing of the origin of these latter sources or the energy spectrum above about 1 GeV, any estimates of high energy neutrino fluxes would be very speculative.

For the pulsars, there seems to be no strong evidence for anything but a pulsed component except for the Crab pulsar (0531+21). Even here the fraction of the total γ-radiation which is constant is decreasing with energy, as shown in Figure 7, with no positive evidence for a non-pulsed component above a GeV. The pulsed component is most usually attributed to curvature of synchrotron radiation, particularly in view of the radio emission and the pulsed nature of the emission. The most intense γ-ray pulsar, as observed at the Earth, is the Vela pulsar (0833-45), first seen by SAS-2 (Thompson et al., 1975) with its double-pulse structure and neither pulse in phase with the radio pulse. The most recent data from 0833-45 (Bennett et al., 1977) is shown in Figure 8. There is, then, clear evidence that charged particles are accelerated; however, there is no absolutely certain evidence from the γ-ray data for a detectable level of

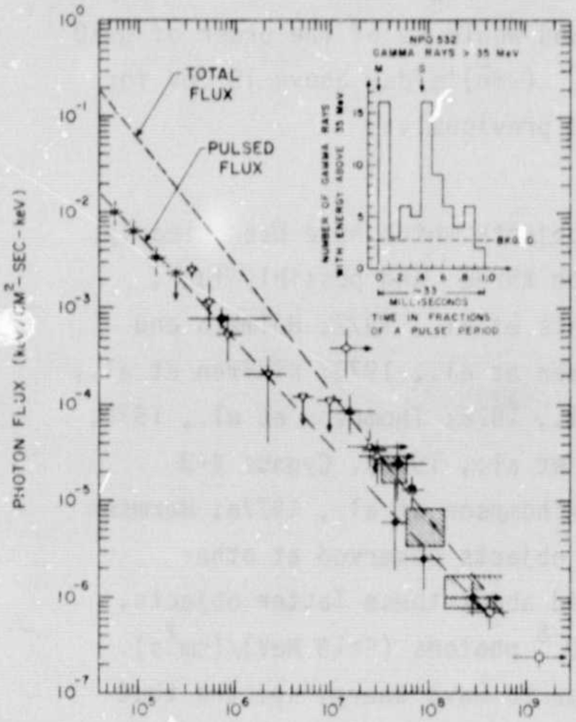


FIGURE 7: Spectrum distribution of fluxes observed from the region of the Crab nebula. The upper dashed line is a curve deduced from x-ray data for the total flux, and the lower dashed line is a similar curve for the pulsed flux only (Laros, Matteson and Pelling, 1973). The symbols are related to other work as follows:

▭ - total flux, Kniffen et al., 1974;
● - pulsed flux, Kniffen et al., 1974;
▽ - Kurfess, 1971;
□ - McBreen, 1973;
○ - Helmken and Hoffman, 1973
▲ - Albats et al., 1972
■ - Browning, Ramsden and Wright, 1971;
◇ - Kinser, Share and Seeman, 1973;
△ - Parlier et al., 1973;
◆ - Orwig, Chupp and Forest, 1971;
✱ - Fishman, Harnden and Haymes, 1969;
T - Ketteuring et al., 1971.

interactions between very high energy relativistic particles and the material in the vicinity of the pulsar. The upper limits are then similar again to those calculated in Section II.

The concept that a pulsar is capable of accelerating particles to very high energies without energy loss inside a very thick shell while still very young has been proposed. Although at very early times this shell would absorb the γ-rays, it would very quickly become thin enough for the γ-rays to be seen also. Hence, this concept seems worthy of theoretical study, both in relation to γ-ray and neutrino astronastronomy.

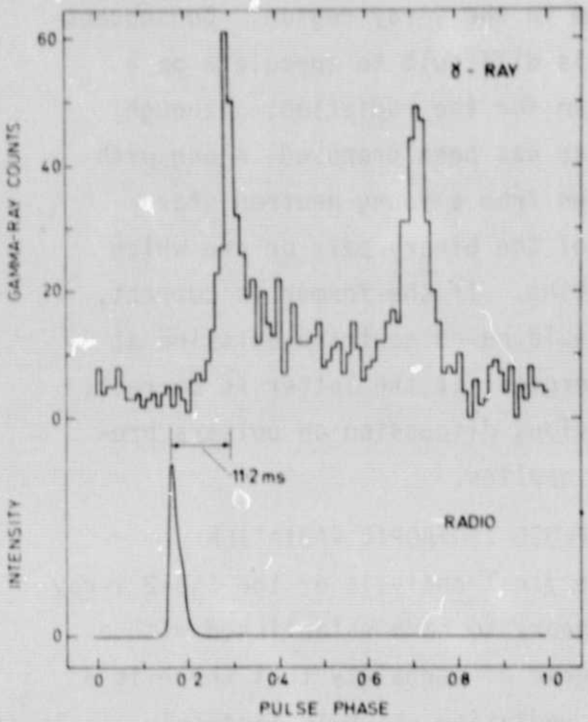


FIGURE 8: Number of γ-rays detected from the direction of PSR 0833-45 with energies above 35 MeV by the SAS-2 γ-ray detector as a function of the time in the pulsar period (Bennett et al., 1977; see also Thompson et al., 1977b).

It should be noted here, however, assuming that pulsars are one of the end products of a supernova explosion, and assuming that rapid nuclear synthesis does occur in a supernova, low-energy neutrinos in detectable amounts, at least from a supernova in this galaxy, should be present (as noted, for example, by Berezinsky and Prilutsky, 1978). The pulse of neutrinos, if detected by an instrument capable of detecting low-energy neutrinos, could be a useful signal for telescopes at other wavelengths to begin observing a specific region of the sky.

Cygnus X-3 is often thought to be a binary system including a neutron star. If it is, it represents the only example observed thus far of γ-radiation from such a system. The γ-radiation shown in Figure 9 (Lamb et al., 1977) has the same period as the x-ray emission. Assuming Cygnus X-3 to be 10 kpc away, it is the most luminous galactic γ-ray source observed so far in γ-rays; however, it is quite far away and appears to be variable. Hence little is known about the spectrum in the γ-ray region. Consequently, it is difficult to speculate on a mechanism for the radiation; although accretion has been proposed, along with radiation from a young neutron star--either of the binary pair or one which is nutating. If the former is correct, there would be no neutrino emission at high energies; if the latter is correct, the previous discussion on pulsars presumably applies.

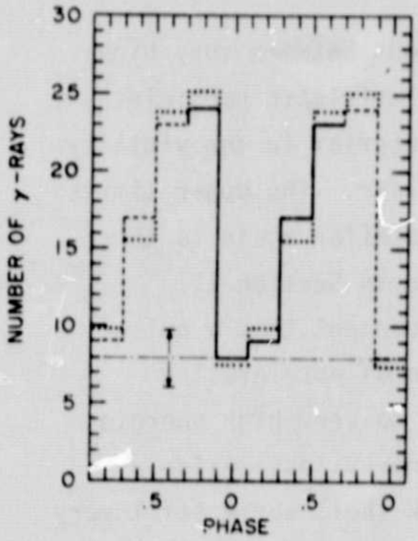


FIGURE 9: The number of γ-rays observed from Cygnus X-3 by SAS-2 as a function of the 4.8-hour phase (Lamb et al., 1977).

## V. DIFFUSE ISOTROPIC RADIATION

The final analysis of the SAS-2 γ-ray data appears to have established with a high degree of certainty that there is a diffuse radiation which is isotropic, at least on a course scale (Fichtel, Simpson and Thompson, 1978), suggesting the strong possibility of a broad extragalactic γ-radiation. The high energy "isotropic" conponent was found to have the following properties: (1) an energy spectrum which is quite steep, with a 2.70 (+0.45, -0.30) differential power law index for a best-fit straight ( $5.7 \pm 1.3) \times 10^{-5}$ photons $cm^{-2}$ $sr^{-1}$ $s^{-1}$; and (3) an extrapolated intensity at 10 MeV which agrees well with the diffuse intensity measured at low energies, about which there is still some uncertainty due to the background difficulties. Figure 10 summarizes the experimental information. The degree of isotropy already established appears to eliminate spherical galactic halo models, unless the halo is assumed to be very large (having a radius larger than 45 kpc) or have a low cosmic ray density.

Among the extragalactic theories, primordial black hole emission (Page and Hawking, 1976), universal primordial cosmic ray interactions (stecker, 1971), interactions of cosmic rays leaking from galaxies (e.g., Felten, 1973), and emission from normal galaxies (e.g., Strong, Wolfendale and Worrall, 1976) all face the combined problems of the steep energy spectrum and the intensity level. Specifically, if it is assumed that normal galaxies are represented by our own, the galactic γ-ray emission above 100 MeV would be inadequate by as much as two orders of magnitude;

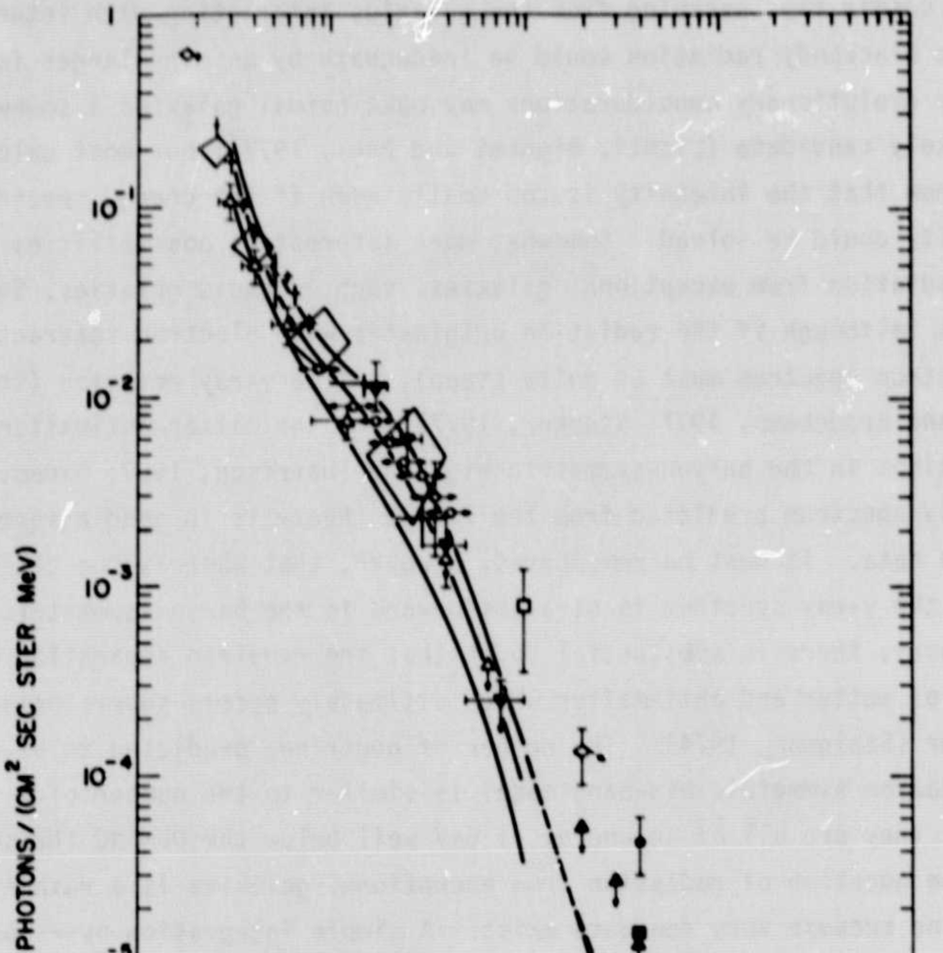


**FIGURE 10:** γ-ray spectrum for the "isotropic" celestial component (from Fichtel, Simpson and Thompson, 1978).

and the cosmic rays escaping from the galaxies interacting with intergalactic blackbody radiation would be inadequate by an even larger factor. Galactic evolutionary considerations may make normal galaxies a somewhat more likely candidate (Lichti, Bignami and Paul, 1977); but most calculations show that the intensity is too small, even if the energy spectra difficulty could be solved. Somewhat more interesting possibilities appear to be radiation from exceptional galaxies, such as radio galaxies, Seyferts and QSOs (although if the radiation originates with electron interactions, the electron spectrum must be quite steep), or the $\gamma$-ray emission (Stecker, Morgan and Bredekamp, 1971; Stecker, 1977) from the matter-antimatter interactions in the baryon-symmetric big-bang (Harrison, 1967; Omnes, 1969). The $\gamma$-ray spectrum predicted from the latter theory is in good agreement with the data. It must be remembered, however, that whereas the calculation of the $\gamma$-ray spectrum is straightforward in the baryon-symmetric big-bang theory, there is substantial doubt that the required separation into regions of matter and anti-matter which ultimately become superclusters can occur (Steigman, 1974). The number of neutrinos predicted to be emitted in the baryon symmetric big-bang model is similar to the number of $\gamma$-rays; however, they are all of an energy <1 GeV well below the DUMAND threshold.

The question of radiation from exceptional galaxies is a rather speculative one because very few data exist. A simple integration over space including cosmological effects and using CEN-A and NGC 4151 as "typical active galaxies" leads to a spectrum and intensity for the diffuse $\gamma$-radiation, which at least makes the concept plausible. The very steep energy spectrum above a few MeV observed in the diffuse radiation arises naturally; and the lower spectral slope below an MeV is also explained, provided the integration is not taken too far back in time. ($Z_{max}$ equal to 3 or 4 is consistent with the data.) If the higher intensity of NGC 4151 whould prove to be correct and representative, only a fraction of the Seyferts would be required to explain the observed diffuse radiation. Thus until further evidence is available, active galaxies must remain a possible explanation for the diffuse $\gamma$-radiation in the 1 to $10^2$ MeV range. So little is known about the high energy region that it seems not very profitable to try to estimate a possible diffuse neutrino intensity based on this concept.

The experiments carried aboard the Gamma Ray Observatory should do much to clarify the nature of the diffuse radiation by obtaining significantly better data on the energy spectrum and degree of isotropy.